A Low-Frequency Radio Sky Survey from Space

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1. Introduction

The frequency range below 30 MHz has not been explored with high angular resolution due to the opacity and refraction of the Earth's ionosphere. An interferometer array in space could provide high dynamic range images of the entire sky with arcminute angular resolution. This would allow a wide range of problems in solar, planetary, galactic, and extragalactic astronomy to be attacked. In addition, it is likely that completely unexpected objects and emission processes will be discovered by such an instrument, as has often happened when high resolution astronomical observations first become possible in a wide new region of the electromagnetic spectrum. True exploration, although difficult to quantify, is one of the most exciting aspects of a mission to survey the low frequency radio sky.

The fundamental technique needed to obtain high angular resolution at very low radio frequencies is aperture synthesis, in which interferometric data from a large number of baseline lengths and orientations are combined to produce images with an angular resolution comparable to that of a single telescope aperture the size of the entire interferometer array. The lowest usable frequencies ($\sim$ 30 kHz) are determined by the local plasma frequency of the interplanetary medium, while the highest frequencies ($\sim$ 30 MHz) are determined by the fact that at higher frequencies aperture synthesis imaging from the ground is possible most of the time. The window between 30 kHz to 30 MHz spans three orders of magnitude in frequency, wider than the infrared window opened by IRAS and ISO or the ultraviolet window opened by IUE and EUVE. It represents the last region of the spectrum which is inaccessible from Earth and still largely unexplored.

2. Science Goals

The primary goal is to map the entire sky at several frequencies in the 0.3-30 MHz range with angular resolution limited only by scattering in the interplanetary and interstellar plasma. Sensitivity and dynamic range should allow $> 10^3$ individual galactic and extragalactic sources to be detected. Some of the specific scientific goals of the sky survey are:

- Search for new sources of coherent radio emission. Coherent emission processes are generally more important at long wavelengths, where the wavelength becomes larger than the typical distance between radiating particles. The Sun, giant planets, and the Earth's magnetosphere all display extremely strong coherent emission at low radio frequencies, and it is quite possible that similar collective plasma processes can produce very high brightness temperatures in objects such as the Crab Nebula, Seyfert galaxies, and quasars. At present, pulsars and circumstellar masers are the only objects outside our solar system which are known to radiate coherently. The best way to detect coherent emission from objects outside the solar system will be spectral shape and in some cases circular polarization.

- Search for new populations of very steep spectrum radio sources. Serendipitous discoveries with this array are likely.

- Determine the volume emissivity distribution in our galaxy by measuring emission from lines of sight to nearby opaque HII regions. Dense HII regions completely block more distant radiation, so if the distance to the HII region and its electron temperature are known the synchrotron emission per unit path length can be determined (for an example, see Kassim, 1990). Low frequency (<30 MHz) radio observations with sufficient angular resolution to resolve dense HII regions offer the only way to directly measure the space density and distribution of cosmic ray electrons with energies below 1 GeV.

- Measure the galactic nonthermal emission from relativistic cosmic ray electrons (e.g., Kassim, 1988). The electrons producing synchrotron radio emission from the galactic disk at frequencies below 30 MHz are the same electrons which produce low energy gamma-rays via bremsstrahlung with interstellar hydrogen nuclei. The synchrotron emissivity depends on the density of relativistic electrons and the interstellar magnetic field, while the gamma-ray emissivity depends on the same electron density and the interstellar hydrogen density. (See above for a discussion of how synchrotron emissivity can be measured.) Thus, by comparing low frequency radio and low energy gamma ray measurements we can find relationships between interstellar magnetic field strength and hydrogen density. Any independent determination of one of these parameters will allow a unique solution for the other.

- Study radio wave scattering by the interstellar medium and determine the turbulence properties of the interstellar plasma. For paths which pass only through the diffuse "type A" interstellar scattering medium (Cordes, Weisberg, and Boriakoff, 1985) it should be possible to directly measure the inner scale of the turbulence. This is not possible with ground- based VLBI arrays operating at much higher frequencies because the scattering disk at high frequencies is too small to resolve with Earth baselines. Only scattering by the clumpy "type B" component of the interstellar medium is observable with ground-based VLBI. Determination of the inner scale for type A scattering would help identify the physical properties of the plasma responsible.

- Determine the galactic distribution of diffuse ionized hydrogen by measuring free-free absorption of radiation from a large number of bright extragalactic sources. Free-free absorption due to intervening ionized hydrogen produces a more steeply inverted spectrum below the turnover frequency than either synchrotron self- absorption or internal free-free absorption, and thus it can be distinguished from these other low frequency absorption processes. Measurement of free-free absorption along many lines of sight covering the full range of galactic latitudes and longitudes will allow the large-scale distribution of diffuse HII to be mapped. Ionized hydrogen is "the only major component of the interstellar medium that has not yet been surveyed" (Reynolds, 1990).

- Measure the low frequency spectra of pulsars (e.g., Erickson and Mahoney, 1985). It is not known where the very steep spectra of these objects turns over. Discovery of a low frequency break in their spectra will constrain the emission processes involved. In particular, timing data at higher frequencies provide an upper limit on the size of the coherent emitting region (Phillips and Wolszczan, 1990) while measurement of the low-frequency spectral turn over can provide a lower limit. Some millisecond pulsars will be among the strongest sources in the sky at frequencies of 10 MHz and below.

- Image galactic supernova remnants and determine their spectra (e.g., Erickson and Perley, 1975). Observations of supernova remnants at low frequencies will test the hypothesis that these objects are the source of cosmic rays. Shock acceleration in supernova remnants has long been thought to produce the observed high energy cosmic rays, but only observations at low radio frequencies can detect (via their synchrotron emission) the presence of the relatively low energy electrons which need to be available for injection into the shock acceleration mechanism.

- Search for "fossil" radio components associated with presently radio quiet galaxies (e.g., Goss, et al., 1987; Cordey, 1987). Are there significant numbers of galaxies which had active nuclei in the distant past but are now quiescent? The very long radiative lifetimes of electrons at low frequencies will preserve evidence of early phases of activity in galaxies which are too faint at higher frequencies to be included in existing radio source catalogs. The discovery of a significant number of "fossil" radio galaxies would be an important new constraint on theories of radio source evolution and lifetimes.

- Determine the distribution of low-energy cosmic rays in nearby (angularly large) galaxies from measurements of surface brightness. For the brightest resolved sources, variations in spectral index can be mapped (e.g., Perley and Erickson, 1979; Winter, et al., 1980). This provides information on the evolution of the relativistic electrons in these sources, such as their diffusion time away from the galactic disk (and thus the strength of the interstellar magnetic field) and the extent of the cosmic ray halo.

- Measure (and map) the radio spectra of extended emission associated with individual radio galaxies such as Centaurus A, M87, and NGC 1275 (3C84). These sources can be mapped with sufficient angular resolution to determine spectral index distributions and filling factors. By measuring the turn-over frequencies we can determine magnetic field strengths and particle radiative lifetimes as a function of position. This will provide unique information on source evolution and lifetime.

Detailed discussions of each of these topics have been published in journals (e.g., Weiler et al., 1988), conference proceedings (e.g., Low Frequency Astrophysics from Space, 1990, ed. Kassim and Weiler, published by Springer-Verlag), and previous low-frequency radio astronomy mission studies (e.g., Dennison et al., 1986; Mahoney et al., 1987; Burns et al., 1989).

3. The Need to go to Space

A crucial question for any proposed low frequency interferometer array in space is whether the science goals listed above really require space-based observations. Ground-based radio arrays have operated at frequencies down to 2 MHz (Ellis, 1972), and a remarkably sensitive survey of the northern sky above declination 60 degrees has been made at 38 MHz with an angular resolution of a few arcminutes (Rees, 1990). Radio images of the Sun with sub-degree angular resolution have been made at 26 MHz, and some individual galactic sources have been detected at 15 MHz (Mahoney, private comm.). The Giant Meterwave Radio Telescope (GMRT) under construction in India will eventually operate down to 38 MHz with a large collecting area (Swarup, 1991).

However, there is a large difference between being able to observe at a given frequency and being able to observe with the angular resolution, sensitivity, dynamic range, and freedom from interfering signals necessary to answer the scientific questions posed above. No high resolution, high sensitivity images of the sky have been produced from the ground at frequencies below 38 MHz. The opacity, refraction, and scintillation effects of the ionosphere have proven to be too severe. At frequencies above about 30 MHz the situation improves rapidly, but at lower frequencies ground-based arrays will not be able to produce images of the sky with angular resolution or dynamic range within an order of magnitude of that expected from a space-based array. The choice of 30 MHz as the upper frequency limit for space-based observations was made precisely because this is the transition region where ground-based interferometers can begin to operate well as least some of the time. We do not want a large gap in frequency coverage between ground-based images of the sky such as those produced by the Very Large Array at 74 MHz (Kessim, et al., 1993) and those produced by a space-based array.

4. Mission Description

Several designs for low-frequency radio arrays in space have been studied over the years, including Earth-orbiting and lunar-based arrays. The specific design described here is called the Astronomical Low-Frequency Array (ALFA), and is being proposed to NASA as a medium-class Explorer mission to be launched before March 2004.

Sixteen identical small satellites will be deployed from a single deployment and data relay bus (DRB) into an Earth-following heliocentric orbit (SIRTF orbit). The small satellites autonomously spin up and keep their spin axes pointed towards the sun using cold gas thrusters, and have two orthogonal dipole antennas in the spin plane. The satellites will cover the surface of a spherical region approximately 100 km in diameter, thus providing good aperture plane coverage in all directions simultaneously. Precise position control in not required due to the long wavelengths being observed. Data from each satellite is transmitted to the DRB via an omni-directional UHF link, and the DRB will transmit the combined data stream to a ground-based antenna at X-band. By moving far from the Earth ($\sim$ 0.1 AU/year) the problem of terrestrial interference is greatly reduced.

The array will operate in two modes: 1) "snapshot" imaging of strong, rapidly changing sources such as solar and planetary radio bursts and the scintillation of strong background sources, and 2) full aperture synthesis observations in which data taken over one or more years are combined for maximum sensitivity, high dynamic range imaging. In both cases a large number of individual array elements are needed. This is possible by using a flight-proven commercial design as the basis for the individual array elements, resulting in a low development cost and a total mass of only 18 kg for each satellite in the array.

5. Conclusions

The frequency range below $\approx$ 30 MHz is unexplored with high angular resolution due to the opacity of the Earth's ionosphere. An interferometer array in space would provide the first high resolution, high dynamic range images of the entire sky at these frequencies. A mission (the Astronomical Low-Frequency Array) to do this is being proposed to the NASA medium-class Explorer program.

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